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Soil Seed Bank Responses to Postfire Herbicide and Native Seeding Treatments Designed to Control *Bromus tectorum* in a Pinyon–Juniper Woodland at Zion National Park, USA

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The continued threat of an invasive, annual brome (*Bromus*) species in the western United States has created the need for integrated approaches to postfire restoration. Additionally, the high germination rate, high seed production, and seed bank carryover of annual bromes points to the need to assay soil seed banks as part of monitoring programs. We sampled the soil seed bank to help assess the effectiveness of treatments utilizing the herbicide Plateau® (imazapic) and a perennial native seed mix to control annual *Bromus* species and enhance perennial native plant establishment following a wildfire in Zion National Park, Utah. This study is one of few that have monitored the effects of imazapic and native seeding on a soil seed bank community and the only one that we know of that has done so in a pinyon–juniper woodland. The study made use of untreated, replicated controls, which is not common for seed bank studies. One year posttreatment, *Bromus* was significantly reduced in plots sprayed with herbicide. By the second year posttreatment, the effects of imazapic were less evident and convergence with the controls was evident. Emergence of seeded species was low for the duration of the study. Dry conditions and possible interactions with imazapic probably contributed to the lack of emergence of seeded native species. The perennial grass sand dropseed outperformed the other species included in the seed mix. We also examined how the treatments affected the soil seed bank community as a whole. We found evidence that the herbicide was reducing several native annual forbs and one nonnative annual forb. However, overall effects on the community were not significant. The results of our study were similar to what others have found in that imazapic is effective in providing a short-term reduction in *Bromus* density, although it can impact emergence of nontarget species.

Nomenclature: Imazapic, brome, *Bromus,* sand dropseed, *Sporobolus cryptandrus* Torr.
Key words: Plateau®, fire, National Park Service.

The interrelationships between invasive plants and fire are recognized as a resource management threat worldwide (Brooks et al. 2004; Zouhar et al. 2008). One example is the grass/fire cycle by which nonnative grass species alter fuel-bed and fire regime characteristics in ways that promote the dominance of invaders over native species (Brooks 2008; D'Antonio and Vitousek 1992). After this alternative stable state has been reached, efforts to reverse it become extremely cost-prohibitive. (Brooks et al. 2004). Most land managers now understand that the best strategy is to prevent the initial establishment of a grass/fire cycle, which may require integrated approaches to control invasive plants following fires (Brown et al. 2008; Humphrey and Schupp 2002).

Cheatgrass (*Bromus tectorum* L.) and red brome (*Bromus rubens* L.) are well known for their ability to cause grass/fire cycles (D'Antonio and Vitousek 1992). Their aboveground biomass dries early in the growing season and persists into the summer fire season, promoting fires at drastically reduced return intervals that native species are often poorly adapted to survive (Brooks et al. 2004; Meyer et al. 2007;

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Management Implications

Invasive annual bromes threaten native diversity across vast areas of the western United States. A variety of techniques have been employed to control these species, yet populations continue to persist and expand. Recently, some success had been achieved through use of the herbicide imazapic. This study sampled the soil seed banks to evaluate the ability of imazapic and a native seed application to reduce brome occurrence and promote native species reestablishment following a wildfire at Zion National Park, Utah. This study is one of the few that has monitored the effects of imazapic and native seeding on a soil seed bank community. Target brome species were significantly reduced during the first year following application, but not during the second and third years. Several nontarget species were also reduced, but overall, the effect on the entire soil seed bank community was not significant. Our results also suggest that imazapic may have had an adverse effect on the emergence of at least two of the seeded native species. However, in general the seeded native species made only a minimal contribution to the soil seed bank and had a minimal effect on reducing brome species, although the increase in sand dropseed during the last year of study suggests that it may become a more substantial component of the seed bank in the next few years. Further research needs to be conducted both on the susceptibility of native species and on the timing of seeding additions in relation to imazapic applications. Finding additional site-adapted natives that can quickly replenish fire-impoverished seed banks would also be beneficial. Finally, the increase in nonnative species in the last year of the study suggests that further steps need to be taken to insure native establishment during the first year of imazapic application.

Stewart and Hull 1949). Seeds from these *Bromus* species often escape lethal temperatures by being positioned at or immediately below the soil surface where fire temperatures are much lower than in the flaming zone, especially within intershrub microhabitats (Brooks 2002). They can then proliferate by growing to great size in the reduced competitive environment of postfire landscapes and producing large quantities of seed, which either germinate in the fall or carry over in the seed bank to germinate in the following spring (Smith et al. 2008). Germination typically occurs well in advance of most native species, allowing the *Bromus* to deplete soil moisture, which can be extremely limiting in semiarid environments (Floyd et al 2006; Melgoza et al. 1990; Smith et al. 2008). Seedling emergence can occur under a variety of soil temperatures and plants germinating in the fall continue to experience root growth during the winter. This gives individuals a significant advantage the following spring (Beckstead et al 2007; Mack and Pike 1983; Meyer et al 2007; Thill et al. 1979).

Efforts to prevent the grass/fire cycle have focused on seeding of species that can compete with and indirectly suppress *Bromus* grasses, and herbicides that can directly kill them. Seeding alone often fails due in large part to competition from nonnative species at the seedling stage (Brooks 2005; Davison and Smith 2007). Previous methods to reduce competitive effects of invasives prior to seeding treatments (plowing, disking, early summer prescribed fire) have had mixed results, but were often not sufficient, especially when trying to control many species of annual bromes (Canode et al. 1962; Evans et al. 1970; Stewart and Hull 1949). However, greenhouse and field trials have had reported success when using Plateau® (imazapic) to control nonnative annual species (Baker et al. 2009; Davison and Smith 2007; Monaco et al. 2005; Morris et al. 2009; Vollmer and Vollmer 2006).

Imazapic is a selective herbicide used for pre- and postemergent control of annual and perennial grasses and some broadleaf species. It works by inhibiting the production of certain amino acids necessary for cellular growth and protein synthesis. It has an average half-life of 120 d in the soil and is quickly broken down by sunlight when in an aqueous solution.

While in the soil, it forms a weak to moderate bond with the substrate and remains active until metabolized by plants, degraded by soil microbes, or leached from the soil due to elevated precipitation (O'Neil 2008; Tu et al. 2001). Previous studies have indicated that low rates of imazapic applied in the fall are most effective at reducing cheatgrass while minimizing negative impacts on native plants (Baker et al. 2009; Kyser et al. 2007; Shinn and Thill 2002, 2004). There is evidence, however, that imazapic can adversely affect seedling development of some native species, especially in moisture-depauperate, postfire environments (Bekedam 2005). Many questions still exist with respect to imazapic effects in the context of landscape-scale restoration projects.

Currently, Zion National Park, Utah, is conducting and monitoring research focused on *Bromus* species control, imazapic use, and native plant restoration. A study in Zion Canyon looked at various combinations of prescribed fire, mowing, imazapic application, and native seed and their effect on exotic brome species and native establishment. A treatment of fall burns plus imazapic application was most effective at impacting the bromes, but herbicide sprayed in the spring following the burn produced the highest densities of native species (J. Matchett, A. O'Neill, M. Brooks, C. Decker, J. Vollmer, and C. Deuser, unpublished data). Evidence suggested that native species were inadvertently affected when the herbicide was applied before emergence, but less of an effect was recorded with postemergence application (Matchett et al., unpublished data). In addition, a nursery study applied different rates of imazapic (0, 0.3, 0.6, and 0.9 L ha^{-1}) in the presence and absence of brome mulch. The moderate rate of 0.6 L ha^{-1} (50.1 oz ac^{-1}) reduced brome species and had less of an impact on native emergence, but was ineffective when mulch was present (Dela Cruz 2008). This indicated the possibility of using this rate in postfire environments where mulch would be largely absent.

An opportunity arose to test the abovementioned moderate rate in a mulch-free environment in the summer of 2006 when a large wildfire (Kolob Fire) started in the southwestern corner of Zion National Park. Locally abundant cheatgrass and red brome were known to occur within parts of the burned area prior to the fire and large populations were growing on adjacent nonparklands. A prescription was designed that called for spraying imazapic at the desired 0.6 L ha^{-1} and included the application of a native seed mix. Study plots were installed to monitor aboveground and belowground treatment effects. Both brome species are capable of inundating the transient seed bank (seeds germinate in the same season as seed shatter) and the persistent seed bank (seeds overwinter to germinate the following spring or fall) (Smith et al. 2008). This study analyzed the soil seed bank to aid Zion National Park in assessing posttreatment changes in *Bromus* densities, native plant establishment rates, and overall effects of the treatments on the soil seed bank community.

The specific objectives of this study were to (1) gauge the effectiveness of the imazapic treatment on reducing *Bromus* in the soil seed bank, (2) assess the individual species component of the native seed mix both in contributing to overall native plant establishment and in suppressing *Bromus* emergence, and (3) determine nontarget seed bank response to the imazapic treatment during each year of the study.

Materials and Methods

Site Description. This study was conducted within perimeter of the Kolob Fire, which started in June 2006 near the southwestern corner of Zion National Park in southern Utah (37°9.38′N, 113°29.35′W) (Figure 1). The fire burned 4,256 ha (10,517 ac), with the majority (75%) in pinyon–juniper woodland and the remainder in shrub/grassland. The study site was located in a pinyon–juniper woodland dominated by singleleaf pinyon (*Pinus monophylla* Torr. and Frém.) and Utah juniper (*Juniperus osteosperma* Torr.). Soils are well drained and consist of very cobbly loam within the top 5 cm (2.0 in) and gravelly clay loam from 5 cm to 12.5 cm. Parent material consisted of eolian deposits derived from shale and sandstone over residuum weathered from basalt. Slopes range from 2 to 20% (Mortensen et al. 1977). Based on the 30-yr average, the average annual temperature for this region is 16 C (61 F) with 37 d over 38 C and 74 d below 0 C. There is an average of 62 d of measurable precipitation per year, which includes 4 d of snow. Annual precipitation averages 38 cm, the majority of which falls during the winter (October to April) and averages 25 cm during that time (Western Regional Climate Center 2005). Annual precipitation was slightly below average in all years of the study. Winter moisture (December, January, and February) was the major contributor to the overall precipitation in 2008 with far less precipitation falling during the late summer monsoons than occurred in 2006, 2007, or 2009. Weather data were obtained from the Zion Canyon Remote Automated Weather Station which is located 14 km (8.7 mi) southeast of the study site.

Treatment Application. Imazapic was applied via helicopter to 3,422 ha at a recommended rate of 0.6 L ha^{-1} from October 28 through November 6, 2006. Previous prefire vegetation mapping found both cheatgrass and red brome in 70% of plots located throughout the burned area (Kolob Fire Emergency Stabilization and Burned Area Rehabilitation Plan, unpublished data). Seed reserves of native species were thought to be scarce given the long-term presence of these exotics and their ability to monopolize the soil seed bank. To assist native succession, this region received an additional application of a locally harvested native seed mix comprising sand dropseed (*Sporobolus cryptandrus* Torr.), bottlebrush squirreltail [*Elymus elymoides* (Raf.) Swezey], Palmer penstemon (*Penstemon palmeri* A. Gray), and desert mallow (*Sphaeralcea ambigua* A. Gray). This application took place on November 1 and 2, 2006, at a rate of 9.0 kg ha^{-1} (19.8 lb. ac^{-1}). There was a total of 1,800 kg of seed of which 67% was from bottlebrush squirreltail, 24% from sand dropseed, 6% from Palmer penstemon, and 3% from desert mallow. All species are perennial, occurred in the study areas before the fire, and have some ability to compete with cheatgrass (Humphrey and Schupp 2004; Leger 2008).

Study Design. A randomized complete block design was implemented pretreatment with 12 blocks, each containing four plots for a total of 48 plots. Plots were 5 by 30 m (16.4 by 98.4 ft) and contained one of the following randomly assigned treatments: control (untreated), native seed mix only, herbicide only, and a combination of herbicide and native seed. Helicopters were given global positioning system (GPS) coordinates of the control and seeded-only plots and instructed to not spray them with herbicide. A 15-m buffer was established around each plot to provide additional assurance that the plots received their correct treatments, plus the flight lines were checked after applications were completed by downloading and reviewing the GPS receivers that recorded helicopter positions during the treatment period. Accurate dispersal of the native seed mix was deemed to be difficult to achieve with a helicopter given the size and type of the seeding boom. Thus, plots were hand-seeded at a rate consistent with the intended aerial application. Individual plots were separated by at least 30 m and none were closer than 15 m to any road. Initial site selection was based upon stratification of the burned area by treatment type, vegetation type, and geological groupings. All sites were located in areas of high fire severity as these areas were targeted for postfire treatments.

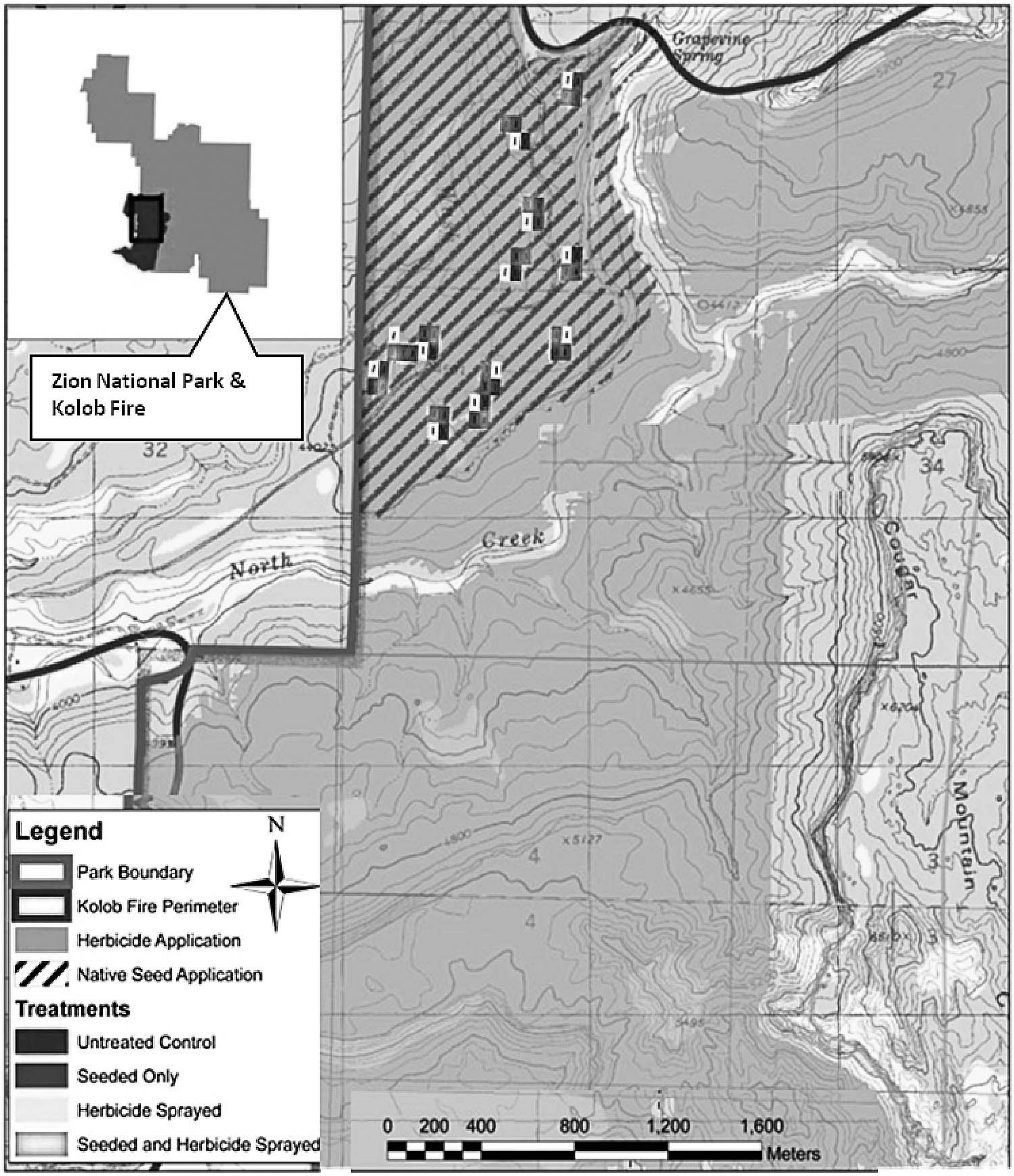

Figure 1. Overview of the study site. The Kolob Fire is shown within Zion National Park and the study site is shown in detail. The shaded area represents the herbicide treatment. Diagonal lines show the extent of the seeding treatment.

Seed Bank Sampling. Seed bank collection was done in late October through early November when soil seed reserves were most replete with available annual and perennial species. Collections were made just prior to treatment application in the fall of 2006 and again in the fall of 2007, 2008, and 2009. Ten samples, each comprising two subsamples, were collected at 5-m intervals along the sides of each plot. To help overcome the spatial anomalies inherent in belowground seed distribution, we collected numerous small samples rather than a few large samples (Bossuyt et al. 2007).

Soil subsamples were collected by pressing a tin soil canister (height 4.4 cm, diam 6.0 cm) into the ground to a depth of 3.0 cm. A metal spatula was then inserted underneath the canister to aid in the removal of a complete sample. Sampling was restricted to the top 3 cm of the soil as previous studies have found few seeds present below 3 cm in desert soils (Ferrandis et al. 2001; Kemp 1989; Price and Reichman 1987). Obstructions such as rocks and woody debris (exceeding approximately 2.5 cm in diam) were removed. Standing vegetation was also avoided. Samples were then placed into a labeled bag and transported to Flagstaff, AZ, where they were placed outside in sealed plastic containers for 2 to 3 mo in order to stratify the seeds. Outside conditions ranged from below freezing to 5 C. Samples were later brought into the greenhouse to be processed for the seed bank emergence portion of the study.

Seed Bank Determination. The contents of the seed bank were ascertained using the emergence method standardized by the U.S. Geological Survey, Western Ecological Research Center. These protocols are based on earlier methods used in the Great Basin (Young et al. 1969; Young and Evans 1978, 1981), but were modified to capture annual plants found in the Mojave Desert (T. Esque, J. Draper, S. Scoles, J. Young, and M. Brooks. unpublished data; Belnap et al. 2008). Many of these same annuals occur at our study site.

Soils were brought out of storage, air-dried and then screened (2-mm [0.08-in] mesh). Stones and organic debris were discarded after first removing any adhering soil. We then mixed 0.12 L (0.5 cups) of the sifted sample with 0.12 L of vermiculite to increase water retention. Each mix was placed in a 15-cm bulb pot lined with synthetic weed-block fabric. Pots were randomly placed on greenhouse benches and watered. Temperature in the greenhouse was monitored but not regulated. Readings ranged from a low of 5 C to a high of 20 C during the winter months and 10 C to 30 C in the summer. No artificial lights were used. All viable seeds in each sample were coaxed to emerge and seedlings were identified, tallied, and plucked. Given that distinguishing between cheatgrass and red brome can be difficult at the seedling stage, they were collectively identified as *Bromus.* This process continued until germination had mostly ceased (4 to 6 wk). The soil mixtures were allowed to dry out for 2 to 3 wk followed by a second watering phase (3 to 4 wk). This pattern was repeated two more times with potassium nitrate (50 ml per pot at a 0.01 M solution) added at the beginning of the third phase (2 to 3 wk) and gibberellic acid (50 ml per pot at a 6.5×10^{-4} M solution) added at the beginning of the fourth phase (2 to 3 wk). The dry-down period approximates natural moisture fluctuations necessary for germination to occur in some desert species (Baskin and Baskin 2001; Meyer et al. 2007). The chemical additives were included due to their previously documented ability to stimulate germination in perennial species (Baskin and Baskin 2001; Bell et al. 1995; Jones and Nielson 1992). Nomenclature for all emerging species followed that of the U.S. Department of Agriculture, Natural Resources Conservation Service (2009).

Data Analysis. All analysis was performed using PC-ORD 5.31 (MJM Software Design, Gleneden Beach, OR). To aid in analysis, all seeded species were grouped together. Permutational multivariate analysis of variance (PerMANOVA) was used to detect differences in *Bromus* and seeded species emergence across the four treatments at each site in each year of the study (Euclidean distance: 4,999 permutations). This ANOVA technique generates a pseudo-F statistic using permutations of the observations, thus allowing for the inclusion of nonnormal data and multiple distance measures (Anderson 2001). This pseudo-F statistic is what is reported in this paper. Detection of a significant treatment effect ($\alpha = 0.05$), was followed by posthoc pairwise comparisons that allowed for a more detailed treatment analysis. PC-ORD does not correct the P values for multiple comparisons.

In order to help characterize the seed bank community associated with each treatment, we compiled data and ran additional PerMANOVA tests pertaining to life history (annual and perennial), growth form (forb and grass), and nativity (native and nonnative). In addition, indicator species analysis (ISA) was performed in order to detect which species were driving between-treatment differences in the overall soil seed bank community (Monte Carlo: 4,999 permutations). This test combines abundance and frequency values to produce an indicator value. Indicator values demonstrate the constancy and exclusiveness of a species to a given group. A Monte Carlo test determines the statistical significance of these values (McCune and Grace 2002). Finally, nonmetric multidimensional scaling (NMS) ordinations were used to visually assess any patterns emerging from PerMANOVA and ISA. NMS is a robust ordination method that makes use of plant-occurrence data to select the axes that best explain variation in community composition (Elmendorf and Moore 2007).

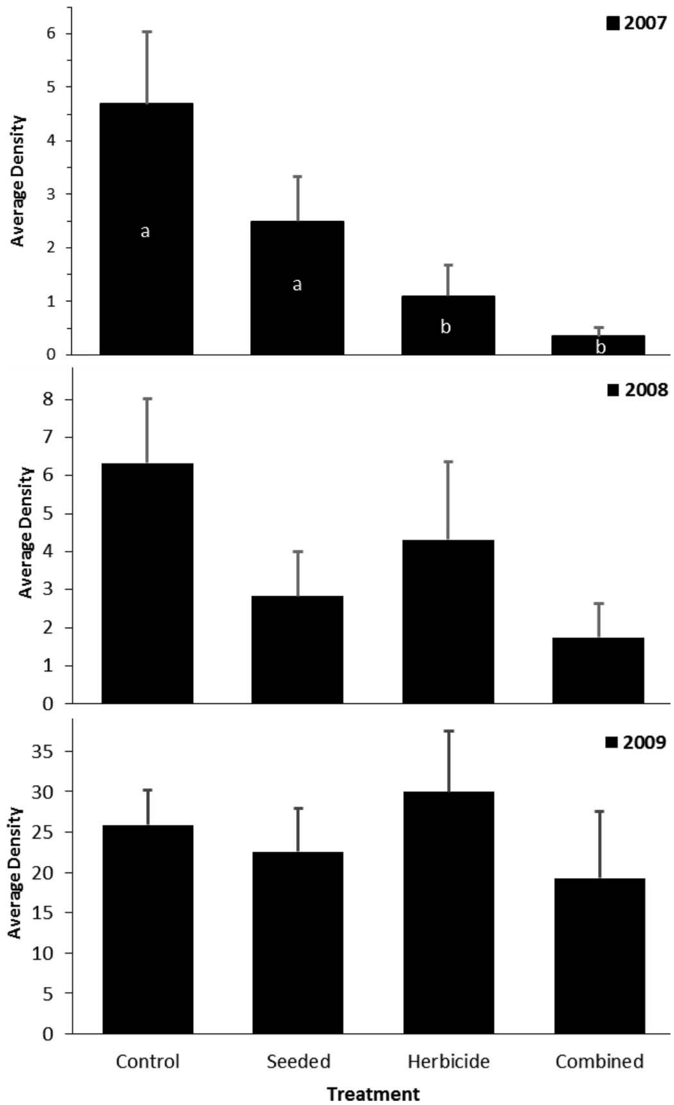

Figure 2. Average seed bank density (based on emerged seeds per 0.12-L sample) of *Bromus*, by treatment, for 2007, 2008, and 2009 with standard error bars. Means sharing a letter do not differ at $P < 0.05$. There were no significant differences for 2008 and 2009.

Results and Discussion

Effects of Imazapic on Reducing *Bromus*. A significant treatment effect was evident in 2007, the first year following treatment application ($df_{3,47}$, $F = 7.45$, $P = 0.0008$) (Figure 2). Average seed bank density that year was significantly lower in herbicide-only and combined plots, compared to the seeded-only and control plots. *Bromus* density was lowest in the plots containing a combination of herbicide and native seed. This first-year response to imazapic is consistent with the findings of previous research (Baker et al. 2009; Bekedam 2005; Kyser et al. 2007; Vollmer and Vollmer 2006). By 2008, the second posttreatment year, nearly all imazapic plots showed some level of increase of *Bromus* in the seed bank. Differences between treatments were not significant in 2008 or 2009.

Our findings suggest that imazapic is a reasonable option for creating a short-term restoration window in invaded areas. However, the resurgence of *Bromus* in the second year following herbicide application indicates the need for subsequent treatments barring the successful establishment of native species within this time frame.

Native Seed Performance. Density of seeded native species was negligible both in 2007 and 2008 (Figure 3). In the first year, only 18 seedlings emerged from the soil samples among all the treatments, representing less than 0.5% of total community composition. In the second year, there was nearly a fivefold increase (85 seedlings) in total seeded species emergence, but seeded species were still a minor component of the seed bank (1.9% of total community composition). The overall increase was largely driven by sand dropseed, which represented 86% of total seeded native species. In 2007, there was an overall treatment effect with the seeded-only plots having significantly higher densities of seeded native seedlings than the herbicide-only plots ($df_{3,47}$, $F = 4.01$, $P = 0.014$ (Figure 3). In 2008, an overall treatment effect was still evident. In the last year of the study (2009), the seeded species emergence continued to increase, but as the rate of emergence was fairly consistent for all treatments, we did not find a significant treatment effect.

The general lack of seeded native species in the soil seed bank was likely due to a combination of factors. All four species in the seed mix were observed producing seeds during the course of the study. However, it is possible that seeded plants had yet to contribute any substantial amount of seed to the soil seed bank as it typically takes from 2 to 3 yr for seeded perennial species to become established in semiarid environments (Humphrey and Schupp 2002). Distribution was patchy and tended to be in low-lying areas, indicating that precipitation events may have relocated seed following application of the treatment (A. Thode, K. Weber, K. Haubensak, H. Brisbin, and M. Brooks. 2011, unpublished data). Several late-fall rain storms did occur shortly after the seeding had taken place. In 2008, density of seeded species was higher in the seeded-only plots when compared to the combined plots suggesting that a negative interaction with imazapic may have also played a role in reducing emergence. Precipitation was well below average during this year as well. The relative success of sand dropseed is best explained by its tendency to produce large quantities of highly germinable seed (Coffin and Lauenroth 1989; Humphrey and Schupp 2001). This grass was the seeded species most frequently observed in the field following treatment application.

Community Analysis. *Description of Soil Seed Bank Community.* A total of 30,228 seedlings emerged from

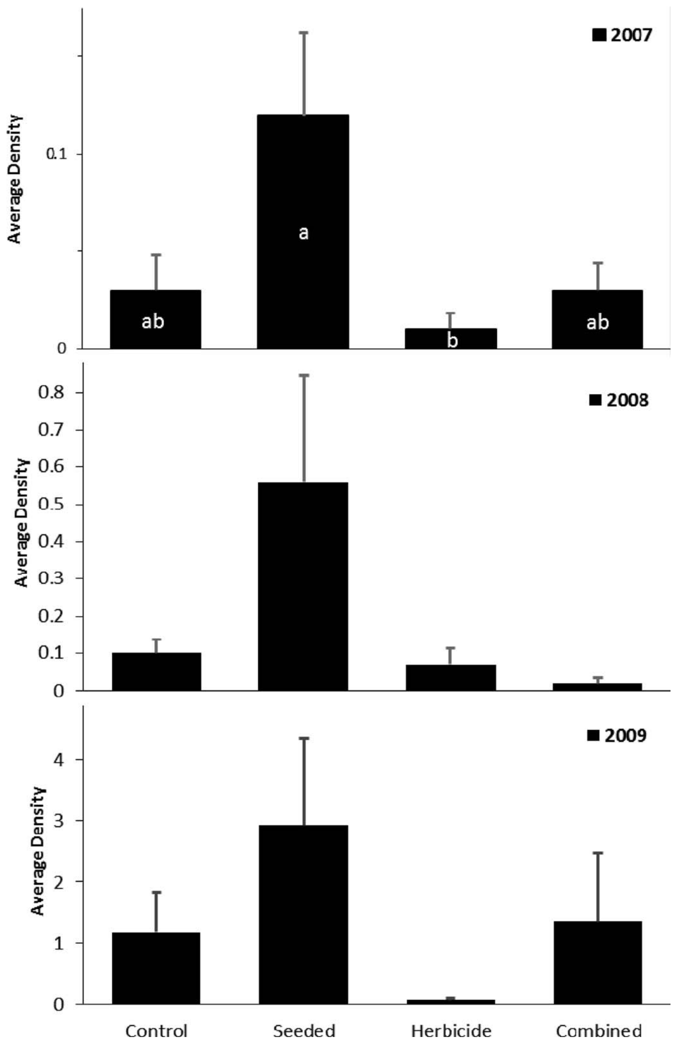

Figure 3. Average seed bank density (based on emerged seeds per 0.12-L sample) of seeded native species, by treatment, for 2007, 2008, and 2009 with standard error bars. There was a significant overall treatment effect for 2008, but no significant pairwise comparisons. This may be due to variance in emergence between plots. For example, density of sand dropseed was high in some plots but absent in others. There were no significant differences for 2009.

the soil samples from 2006 to 2009, representing 47 species from 25 different families (Table 1). Annual species represented 92.9% of total seedlings, perennials represented 3.6%, and biennials represented 3.4%. A similar proportion was evident for each individual year. Of all the species, 37 (78.7%) were forbs, 6 (12.8%) were grasses, and 4 (8.5%) were shrubs. Eight nonnative species (17%) were present, including cheatgrass, red brome, tumble pigweed (*Amaranthus albus* L.), redstem filaree [*Erodium cicutarium* (L.) L'Hér ex Aiton], forage kochia [*Bassia prostrata* (L.) A.J. Scott], prickly lettuce (*Lactuca serriola* L.), bur buttercup [*Ceratocephala testiculata* (Crantz) Roth], and saltcedar (*Tamarix ramosissima* Ledeb.). All species detected in the soil seed bank were in the aboveground community with the exception of rough draba (*Draba asprella* Greene), fringed willowherb (*Epilobium ciliatum* Raf.), saltcedar, and cattail (*Typha angustifolia* L.). The aboveground community was sampled in a complementary study (Thode et al. 2011, unpublished data). The most abundant species throughout the study were cheatgrass, redstem stork's bill, sixweeks fescue [*Vulpia octoflora* (Walter) Rydb.], wedgeleaf draba (*Draba cuneifolia* Nutt. ex Torr. & A. Gray), and prickly lettuce.

Treatment Effects on the Entire Community. PerMANOVA tests detected no significant difference in the soil seed bank communities associated with each treatment type for any year of the study. In 2007, the non-metric multidimensional scaling (NMDS) ordination (two dimensions, stress = 17.8) revealed only a conservative amount of spatial separation within the data between the four treatments (Figure 4). This separation was more apparent when comparing unsprayed plots (controls and seeded-only) to sprayed plots (herbicide-only and combined). Unsprayed plots were also clustered closer together than sprayed plots indicating more uniform composition. Ordinations for subsequent years were inconclusive and had high stress.

Treatment Effects on Groups. There was no significant difference between treatments for any year when analyzing average density of annual species. This was also true for perennial species with the exception of 2008, when an overall treatment effect was detected. Despite a lack of significant pairwise comparisons, the control showed an increase in perennial species over all other treatments. Analysis of forb species revealed significantly more forbs in both the control and seeded-only plots relative to the herbicide-only and combined treatment plots for 2009 (Figure 5). The same was true of nonnative species in 2009 (Figure 6). There were no significant differences for any year when analyzing by grass and native species.

Treatment Effects on Individual Species. The ISA found several species that were demonstrating an affinity for a given treatment (Table 2). PerMANOVA tests were run to see if any of these relationships were significant. In 2007, sleepy silene (*Silene antirrhina* L.), narrowstem cryptantha (*Cryptantha gracilis* Osterh.) and wedgeleaf draba were all indicators for the controls. Of these, a significant treatment effect was evident only for wedgeleaf draba. Density of wedgeleaf draba in the soil samples was significantly higher in the control plots and seeded-only plots relative to the herbicide-only plots. By 2008, only wedgeleaf draba was still an indicator for the controls and sand dropseed was revealed to be an indicator for the seeded-only treatment. A significant treatment effect was found for both species. For wedgeleaf draba, both the controls and seeded-only plots

Table 1. Species list for pinyon–juniper site for all years of the study.

Scientific name	Family	Life form	Life history
Amaranthus albus[a]	Amaranthaceae	Forb	Annual
Amaranthus fimbriatus	Amaranthaceae	Forb	Annual
Astragalus nuttallianus	Fabaceae	Forb	Annual
Bassia prostrata[a]	Chenopodiaceae	Forb	Perennial
Bromus rubens[a]	Poaceae	Grass	Winter annual
Bromus tectorum[a]	Poaceae	Grass	Winter annual
Centaurium calycosum	Gentianaceae	Forb	Annual
Ceratocephala testiculata[a]	Ranunculaceae	Forb	Annual
Chamaesyce albomarginata	Euphorbiaceae	Forb	Perennial
Cirsium neomexicanum	Asteraceae	Forb	Biennial
Claytonia perfoliata	Portulacaceae	Forb	Annual
Conyza canadensis	Asteraceae	Forb	Annual
Cryptantha gracilis	Boraginaceae	Forb	Annual
Cylindropuntia whipplei	Cactaceae	Shrub	Perennial
Descurainia pinnata	Brassicaceae	Forb	Biennial
Draba asprella var. *zionensis*	Brassicaceae	Forb	Perennial
Draba cuneifolia	Brassicaceae	Forb	Annual
Elymus elymoides	Poaceae	Grass	Perennial
Epilobium ciliatum	Onagraceae	Forb	Annual
Eriastrum diffusum	Polemoniaceae	Forb	Annual
Erigeron divergens	Asteraceae	Forb	Biennial
Eriogonum palmerianum	Polygonaceae	Forb	Annual
Erodium cicutarium[a]	Geraniaceae	Forb	Winter annual
Gilia inconspicua	Polemoniaceae	Forb	Annual
Gutierrezia sarothrae	Asteraceae	Shrub	Perennial
Lactuca serriola[a]	Asteraceae	Forb	Biennial
Layia glandulosa	Asteraceae	Forb	Annual
Lepidium lasiocarpum	Brassicaceae	Forb	Annual
Lotus denticulatus	Fabaceae	Forb	Annual
Lotus humistratus	Fabaceae	Forb	Annual
Lupinus kingii	Fabaceae	Forb	Annual
Microseris lindleyi	Asteraceae	Forb	Annual
Mimulus rubellus	Scrophulariaceae	Forb	Annual
Myosurus cupulatus	Ranunculaceae	Forb	Annual
Penstemon palmeri	Scrophulariaceae	Forb	Perennial
Phacelia fremontii	Hydrophyllaceae	Forb	Annual
Physalis heterophylla	Solanaceae	Forb	Perennial
Plantago patagonica	Plantaginaceae	Forb	Annual
Poa secunda	Poaceae	Grass	Perennial
Purshia mexicana	Rosaceae	Shrub	Perennial
Silene antirrhina	Caryophyllaceae	Forb	Annual
Sphaeralcea ambigua	Malvaceae	Forb	Perennial
Sporobolus cryptandrus	Poaceae	Grass	Perennial
Tamarix ramosissima[a]	Tamaricaceae	Shrub	Perennial
Typha angustifolia	Typhaceae	Forb	Perennial
Vicia ludoviciana	Fabaceae	Forb	Annual
Vulpia octoflora	Poaceae	Grass	Annual

[a] Nonnative species.

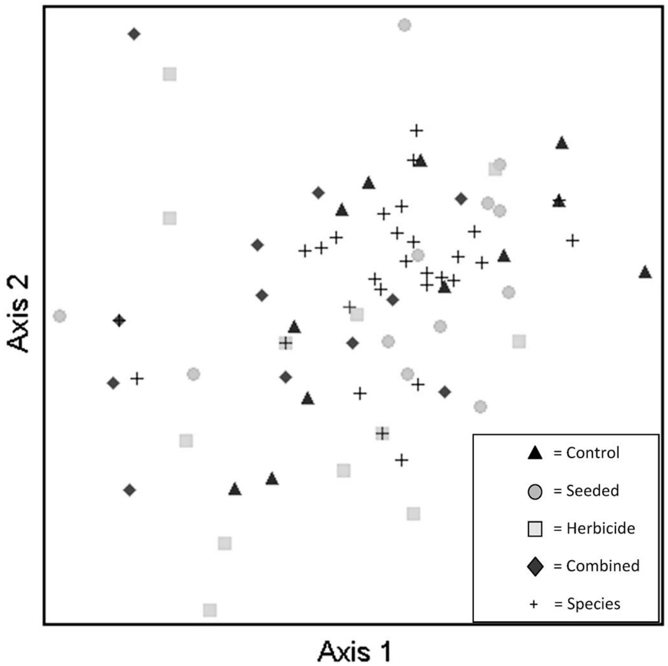

Figure 4. Nonmetric multi-dimensional scaling plot of soil seed bank communities in 2007. Individual symbols represent individual plots. This configuration was determined using the abundance of 30 species on 48 plots.

had significantly higher densities than the combined plots. In the seeded-only plots, the density of sand dropseed was significantly higher than in the combined plots. In 2009, Canadian horseweed (*Conyza canadensis* L.) and prickly lettuce were both indicators for the herbicide-only treatment, redstem stork's bill was an indicator for the controls, and Lindley's silverpuffs [*Microseris lindleyi* (DC.) A. Gray] was an indicator for the combined treatment. No significance was found for Canadian horseweed or silverpuffs. Redstem stork's bill proved to be significantly

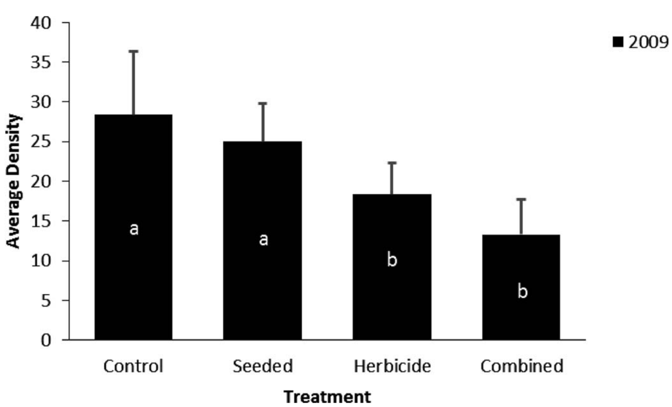

Figure 5. Average seed bank density (based on emerged seeds per 0.12-L sample) of forb species, by treatment, for 2009 with standard error bars. Means sharing a letter do not differ at P < 0.05.

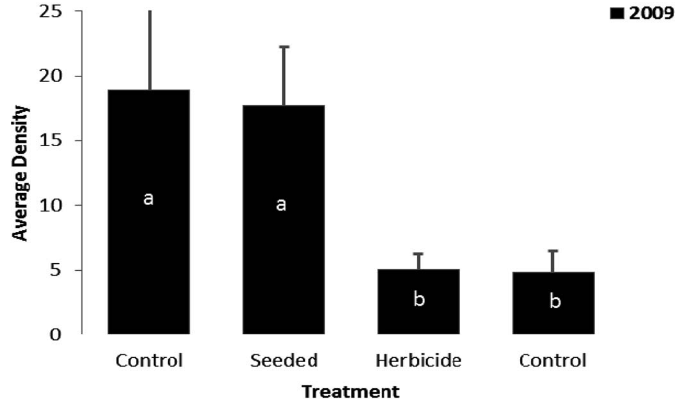

Figure 6. Average seed bank density (based on emerged seeds per 0.12-L sample) of nonnative species, by treatment, for 2009 with standard error bars. Means sharing a letter do not differ at P < 0.05.

more abundant in the controls and seeded-only plots relative to the herbicide-only and combined plots, and prickly lettuce was significantly more abundant in the herbicide-only and combined plots relative to the seeded-only plots.

Community Analysis Summary. At the community level, the treatments did not appear to have much of an effect on the nontarget species in the soil seed bank. However, some general patterns did emerge. For example, most indicator species were indicators for unsprayed plots, meaning that they were both more abundant and occurred with greater frequency in these plots relative to sprayed plots. This suggests that the imazapic may have reduced seedling emergence. Similarly, ordination of the plots in 2007 showed a degree of spatial separation in the data based upon whether plots had been sprayed or unsprayed. This separation was not as apparent in 2008 and 2009, but it is likely that the herbicide was no longer active at this time. Imazapic can persist in the soil for up to 2 yr on vegetation-depauperate sites, but is commonly metabolized by plants within the first growing season following application (Davison and Smith 2007; Tu et al. 2001; Matchett et al., unpublished data). Examination of various groupings was unrevealing aside from showing significantly higher densities of forbs and nonnative species in unsprayed plots in 2009. These results were largely driven by redstem stork's bill. Analysis of individual indicator species also found that prickly lettuce was more abundant in the herbicide-only plots in 2009. It is not uncommon for this plant to become established in pinyon–juniper woodlands following disturbance (Barclay et al. 2004; Kuenzi et al. 2008).

Overall Summary. Although the herbicide treatment did not have a significant impact on the community present at

Table 2. Significant indicator species for the soil seed bank community for 2007, 2008, and 2009. To be significant, species had to have an indicator value of $\geq$ 25 and a P value $\leq$ 0.05.

	Year								
	2007			2008			2009		
Species	Group[a]	IV[b]	P value[c]	Group[a]	IV[b]	P value[c]	Group[a]	IV[b]	P value[c]
Conyza canadensis	—	—	—	—	—	—	Herbicide	40	0.0286
Cryptantha gracilis	Control	32.1	0.0335	—	—	—	—	—	—
Draba cuneifolia	Control	50.9	0.0190	Control	43.8	0.0074	—	—	—
Erodium cicutarium	—	—	—	—	—	—	Control	45.9	0.0338
Lactuca serriola	—	—	—	—	—	—	Herbicide	51.2	0.0086
Microseris lindleyi	—	—	—	—	—	—	Combined	35.5	0.0246
Silene antirrhina	Control	48.0	0.0267	—	—	—	—	—	—
Sporobolus cryptandrus	—	—	—	Seeded	36.5	0.0201	—	—	—

[a] Represents the treatment type for which the species was a significant indicator species.

[b] Abbreviation: IV, indicator value, the percentage of perfect indication, based on combining the values for relative abundance and relative frequency.

[c] P values represent the proportion of randomized trials with IV equal to or exceeding the observed IV.

the study site, our results on individual species and the results of other studies implies that inadvertent control of native species is a reality. Therefore, prudence is recommended when deciding if imazapic is the correct choice for achieving management goals. There still remains a need for finding better ways to restore *Bromus*-dominated systems. Use of the herbicide imazapic shows promise, but further research needs to be conducted both on the susceptibility of native species in general and on the timing of seeding additions in relation to imazapic applications. Finding site-adapted natives that can quickly replenish fire-impoverished seed banks would also be beneficial. This study and others indicate that sand dropseed may fulfill this role in areas where it naturally grows. The increase in nonnative species in the last year of the study suggests that further steps need to be taken to insure native establishment during the first year of imazapic application.

Results from this study support the inclusion of seed bank assays in guiding management decisions and monitoring restoration of areas invaded by annual *Bromus* species. For example, posttreatment assays of the soil seed bank strengthened the results of the co-occurring aboveground study. Data collected from the soil seed bank would be useful in deciding whether or not additional measures, such as herbicide application, should be taken to help restore disturbed areas. If a disturbance (i.e., thinning, prescribed fire) is planned for an area, this same knowledge would provide managers insight on what to expect regarding the release of nonnatives following such an action. The close correlation between summer seed crops and *Bromus* species emergence could allow seed bank assays to supplant aboveground assessments. Access to a greenhouse facility would be necessary, but field collections would require less time and fewer personnel, and soils can be stored for several years with little effect on seed viability (Hulbert 1955).

Future Work Needed. The increase in nonnative species in the last 2 yr of the study further stresses the need to insure native establishment during the first year of imazapic application. As imazapic did appear to at least contribute to the inhibition of native seedling emergence, it may be beneficial to incorporate a time lag between the herbicide application and the application of native seed. For instance, if imazapic is applied in the fall to a highly invaded area, the majority of the herbicide should be metabolized by the target species as it emerges the following spring. Native seed applied in late spring/early summer would then have the opportunity to germinate and grow in an environment with less herbicide and less competition from the target species. However, many of the seeded species would not germinate until winter if sufficient summer moisture was unavailable. In this scenario the seeded species would still be faced with germinating into higher levels of *Bromus*. Long-term monitoring of plant communities treated with imazapic is necessary to better understand the successional trends that may develop. Zion National Park will continue to monitor a portion of the plots established at the Kolob site.

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